

SECTION 27

Agriculture

THERMAL SCANNER DATA FOR STUDYING FREEZE CONDITIONS

AND FOR AIDING IRRIGATION SCHEDULING

by

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PREFACE

There are many applications for infrared thermal scanners in Agriculture because they provide more complete thermal information than can be obtained using point measurements. The Recon IV scanner was used on Mission 117 during the night of January 7 and 8, 1970 under near freezing conditions when five different research agencies were conducting citrus grove heating experiments. Another experiment was conducted for determining plant canopy temperatures as an indicator of drought or need for irrigation. The RS-14 scanner¹ was flown early in July 1970 for this purpose. For ease of presentation, the paper will be divided into two parts, studies during freezing conditions being discussed first.

PART I - NASA MISSION 117 - THERMAL SCANNER RESULTS DURING A
THREATENED CITRUS FREEZE

INTRODUCTION

When freezes severely injure citrus trees and other vegetation, the economy of an agricultural area is adversely affected for several years. In the Lower Rio Grande Valley of Texas severe freezes have occurred in 1930, 1949, 1951, and 1962. Although there is a 50% chance that a severe freeze will occur in the mid-Valley area once every 10 years, the time interval for a severe freeze has ranged from 2 to 19 years. Each of the 3 major freezes killed or severely damaged

¹ Trade names and company names used in this publication are included for the benefit of the reader and do not imply endorsement or preferential treatment of product by U. S. Department of Agriculture.

most of the bearing citrus trees. In the last major freeze (1962), the citrus industry in Texas lost over 17 million dollars, and in Florida the loss was in excess of one-half billion dollars (1).

Since there is no satisfactory method for freeze protection in the Lower Rio Grande Valley, research is needed on efficient ways of adding heat to a grove, of conserving energy contained in the grove, and of classifying land for freeze susceptibility. Information that is obtainable from aircraft-mounted thermal scanners would be very helpful in this type of work.

Freeze protection research is generally conducted in areas of 5 to 30 acres. Temperature is the key parameter, and it is difficult to take enough ground measurements with thermocouples, thermometers, diodes, and thermistors to adequately characterize the temperature in this large an area. On the other hand, a thermal scanner measures the thermal radiation (temperature) of an entire area.

A second need in freeze protection is to classify land areas as to their freeze susceptibility. This classification can be gained by experience through freezes, but it can be done routinely with thermal scanners since they provide information for thermal contouring. Thermal contours classify areas according to freeze susceptibility, show areas where cool air drainage is important, and suggest a means for diverting or modifying the flow of cool air.

A third area where temperature input is required is in determining temperatures throughout the Rio Grande Valley on nights when the freeze hazard is imminent. Temperature measurements are limited, and it is frequently difficult to extrapolate these measurements to large crop growing areas. Also, measurements are of air temperature, and the most important parameter is plant leaf temperature. Thermal scanner data obtained by aircraft flying during freeze hazard conditions could, with rapid data reduction, be used to tell grove managers when critical temperatures were reached, so freeze protection measures could be activated.

The use of infrared scanner information for 3 major purposes (freeze protection research evaluation, mapping freeze hazard areas, freeze protection activation systems) could minimize freeze losses and save millions of dollars.

PURPOSE AND OBJECTIVES OF THE MISSION

Mission 117 was requested to obtain thermal scanner data under freeze conditions in the Lower Rio Grande Valley of Texas where winter freezes are an important crop production hazard. Flight lines were selected over citrus groves that various agricultural research agencies had chosen for heating tests. Temperature variations in other groves along the flight lines were expected as the result of differences in natural air drainage associated with topography, wind breaks, and different cultural practices in the groves. Previous experiments had relied on point temperature measurements in the groves, whereas scanner data offered the possibility of spatial integration of existing temperature conditions.

The specific objectives of the mission were:

- 1) To compare the temperature (irradiance) of a heated portion of a citrus orchard with an unheated portion of the same orchard.
- 2) To determine the effective area of an artificial fog for freeze protection, and the radiation characteristics of the fog.
- 3) To define the general thermal gradient along a 20 mile-long flight line from north to south across the middle of the Lower Rio Grande Valley.
- 4) To relate differences in ground conditions around trees (bare soil, grass sod, gravel mulch) with tree and ground temperatures (irradiance).
- 5) To determine how normal topographic variation and wind breaks affect citrus tree temperatures and air drainage.

PROCEDURE

PREPARATIONS PRIOR TO MISSION

In preparation for the mission, scientists from Texas A&M University, Texas A&I University, Rio Farms, Inc., and the Crops Research and Soil and Water Research Divisions (USDA) met on December 19 to coordinate premission calibration of ground instruments (hygrothermographs, thermometers), deployment of ground instrumentation, establishment of a radio communication network, and the general conduct of 5 separate

freeze protection experiments that would be in progress during the night of the mission. Twenty-five user agency personnel were engaged in conducting the experiments the night the mission was flown.

Also, prior to the mission, the flight lines were overflown at 3,000 feet to take photographs with a 70 mm Hasselblad cluster. Photographic documentation was obtained using Plus-X black-and-white (8401), conventional aerial color (8442), Ektachrome infrared aero (8443), and black-and-white infrared (2424) films.

Extensive discussion took place with NASA and Lockheed (NASA contractor) personnel concerning operating characteristics of the Recon IV scanner, settings of the internal reference temperatures, preflight calibration of the scanner and PRT-5, and scanner imagery and its characteristics desired (linear portion of film gamma function).

CONDUCT OF THE MISSION

The mission was conducted the night of January 7 and 8, 1970 using the C130 aircraft and the Recon IV thermal scanner. Overflights were made at 2100, 2400, and 0300 hrs. Ambient temperature dropped through the evening to about 34°F at 0100 hrs. Around 0300 hrs the wind shifted and increased enough to arrest the temperature decline. The scheduled 0600 hr overflight was cancelled because landing gear trouble developed on the aircraft.

RESULTS AND DISCUSSION

RESULTS PERTAINING TO SPECIFIC OBJECTIVES OF THE MISSION

Objective 1: To compare the temperatures (irradiance) of a heated portion of a citrus grove with the unheated portion of the same grove.

Before extensive digitizing and print-out of digitized values were conducted, it was felt advisable to first intensively investigate one area. The area chosen is frequently referred to locally as A&I grove south. It was on flight line 2 and was overflown at 2,000 ft. Because of technical difficulties, this area was not flown at 2100 or 2400 hrs. However, on the second pass during flight 3 (0355 hrs), the area was overflown shortly after heating had been initiated in two different citrus plantings within the area. Heating consisted of burning 4-lb coke blocks, 2 per tree, in a 7-acre area, and return stack heaters, 40 per acre in an 8 1/2-acre area.

Figure 1 shows a thermal black-and-white photograph obtained from the film produced during the flight. The dark areas are warmer than the lighter-toned areas. The 2 heated citrus areas are designated by arrows. The RS represents the area with return stack heaters, while the other area is the petroleum coke-block-heated area labeled TH ("Tree Heet"). The 2 areas stand out quite clearly, and within each heated area there is considerable density contrast. This contrasting density is particularly noticeable in the return stack heated area, and is believed to be caused by 3 factors. First, the return stack heaters are much larger and burn hotter than the coke blocks. Therefore, there is a greater contrast among the heated areas directly around the heaters and those further away. Second, there is an AC-DC coupling problem that tends to give an overshoot when a warm element is followed by a cool element. Third, the RS heaters were located in the middles between the trees, whereas the TH heaters were located at the "skirts" (edge of the tree canopies). Consequently, tree foliage obscures many of the TH heaters.

Figure 2 shows a thermal photograph of the analog signal that was played onto a CRT scope with a variable Z axis. This picture was taken of the CRT screen by the Data Reduction Group of Lockheed, a NASA Houston subcontractor. This photograph is quite similar to the one produced during the flight. However, the light streak noted along the right side of Figure 1, believed to be caused by the bending of the film exposed in flight, is not observed in Figure 2, and it appears that the RS-heated area in Figure 2 does not have as high a contrast as the same area in Figure 1.

Of particular interest are 2 nonheated areas near the center of Figure 2 that are shown to be slightly warmer. These areas are relatively uniform, darker grey and rectangular in shape, compared with the surroundings. These 2 areas have different cultural practices than the citrus blocks around them. Thus the cultural practice appears to increase the temperature of trees in these 2 nonheated blocks compared with the temperature of trees in surrounding blocks.

Figure 3 is a color enhancement of the black-and-white negative thermal film. In this enhancement, dark blue, light blue, light green, dark green, olive, yellow, brown, red, magenta, violet, and black (grey) colors represent warmest to coolest temperatures in that sequence. In general, the return-stack-heated area shows a greater radiance as observed by the scanner than the area heated with TH. A north wind was blowing at about 1.5 m/sec at one meter above the trees during this overflight. There appears to be a warmer area south of the return-stack-heated area. This warmer area was probably caused by energy that moved downwind from the heated area. Further analysis is required to substantiate this interpretation of the color enhancement. Physically, however, it seems realistic, and thermographs in the downwind area showed a higher temperature than thermographs in a nonheated area east of the grove. Such a downwind effect can be expected from heat transfer theory.

Another warmer area of interest (IF) in the color enhancement, Figure 3, is in the northern part of the photograph. Prior to the flight, this area was irrigated in an attempt to eliminate freeze damage. The blue spot in the middle of the red flood-irrigated portion may have been caused by standing water, since it was the wettest portion of the field when it was examined after the flight.

Figure 4 shows a graph of temperature versus digital count values. The data were digitized by an 8-bit digitizer that gives 0 to 256 counts over a given voltage range. A line is drawn in this figure that connects the temperature from the 2 calibration (cal) sources on the Recon IV. These points are labeled BB1 (Blackbody 1) and BB2 (Blackbody 2). It was immediately obvious from observing the trace of a scan line on the scope, that the cal sources are at a considerably higher temperature than any of the ground truth data. This problem was anticipated, since the cal sources can only be heated and not cooled. However, there was no way to get the cal sources on the Recon IV to bracket the expected ground temperatures. Thus there was no alternative but to accept the blackbody temperatures available, one at near aircraft temperature and one that was slightly heated. Thus extrapolation from the cal source temperature range to the data range was necessary. Based on this extrapolation a great majority of the scanner resolution element temperatures surround 0°C. On Figure 4 the bins are indicated by the alphabetical letters A through O. The bins used in the 1st, 2nd, and 3rd Picout runs are shown. In the initial run, very few alphabetic letters were plotted since most of the data fell in the area where the blank symbol was used. Subsequently, in run 2, the counts corresponding to bins A and B were lowered so that much of the area was assigned symbols in the computer printout. Finally in run 3, the bins are moved down even further, and run 3 has been used to determine the average temperatures as seen by the scanner for the 2 heated areas.

Table 1 shows the distribution of the alphabetic letters for the RS and TH heated areas. In both cases the A's are the most frequently occurring letter as shown by 810 values in the TH area and 734 values in the RS area. The number of entries in the remaining bins decreases rapidly. It would seem to the authors that if the cal source temperatures could have been properly set, the majority of values would fall in the bins midway in the temperature range. With so many values falling in the 0 to a few count area, one has to worry about the statistical distribution of the data.

The number of values in each bin were counted, converted to temperatures, and averaged. The RS heated area corresponds in radiance to an average temperature of 1.1°C, while the TH heated area corresponds in radiance to a temperature of -4°C. Thus, on the average, the temperature of the two areas differed by 1.5°C.

Objective 2: To determine the effective area of an artificial fog for freeze protection and irradiation characteristics of the fog.

This objective was investigated using both radiometers and Barnes thermal camera, and with aircraft data from the thermal scanner. Radiation instruments showed that the fog affected the radiation balance almost insignificantly, and extensive examination of the thermograms produced by the Barnes infrared camera revealed no grey scale variations. Visual observation showed that only a few wisps of the fog penetrated into the orchard from the foggers that were located about 40 feet upwind from the 1st tree row. The thermal film was examined by placing the negative produced during the flight on a Spatial Data Systems Datacolor system. Examination with various settings did not reveal any difference in film optical density (color difference on the TV screen) characteristics in the fogged area. It was concluded that on the particular night of the study the artificial fog produced did not significantly alter radiation characteristics of the area covered by the fog. Since this particular fog had a particle size of about $2 \mu\text{m}$, this finding can be anticipated from radiation theory which suggests that droplet size would have to be concentrated in the 5- to $20\text{-}\mu\text{m}$ diameter range to be most effective.

Objective 3: To define the general thermal irradiance over a distance of 20 miles from north to south across the center of the Lower Rio Grande Valley.

This objective cannot be evaluated from this mission, even though the experiment was designed for this purpose, because two-thirds of the time the scanner was malfunctioning so that the data are discontinuous within flight lines. However, this type of information may be obtainable at some future time.

Objective 4: To relate differences in ground conditions around the trees (bare soil, grass sod, gravel mulch) with tree and ground temperatures (irradiance).

This experiment was to be conducted by use of the thermal scanner over the USDA Research Farm. Even though the Research Farm was overflown 3 times, no good imagery was obtained of that area. However, as mentioned under Objective 1, when discussing Figure 2, it appears that the effects of cultural practices can be evaluated. Figure 5 is included to show that imagery from the Recon IV is sufficiently detailed to show considerable contrast between fields observed below the plane. This figure shows that high contrast and good resolution can be obtained from

the agricultural scene. The outlines of fields are easily observable. Upon closer examination some **warmer (darker)** areas are observable within the fields in this figure. Thus it appears that thermal imagery could shed much light on this objective.

Objective 5: To determine how normal topographic variation and wind-breaks affect citrus tree temperatures and air drainage.

Further investigation into this objective may yield valuable information with the data obtained from this flight. Thus far, we have reached these preliminary conclusions. First, as is shown from Figures 1, 2, and most significantly in Figure 4, large temperature variations occur naturally from field to field, particularly where the fields change in cover such as from a bare soil to a cropped surface. Also, large irradiance changes occur even within a field when there is a moisture variable, since the higher ground may be drier than the low ground. Low ground that is moist stores more heat during the day than higher dry ground. The lower ground, in this case, will be warmer than the higher areas, which is the reverse of what one would expect when significant cold air drainage is a factor. Another factor is that topographic variations are minor in the Lower Rio Grande Valley so that, except under extremely calm, strong radiation conditions, it may be difficult to pick up much thermal variation. There was not a strong temperature inversion the night of the mission. This variation caused by topography would most easily be detected in a large area of relatively uniform cover or cultural condition.

CONCLUSIONS

This mission required the coordination of research by 5 agencies plus the flight by the C130 aircraft with the Recon IV thermal imager and PRT-5 in operation. The objectives laid out for the mission were numerous and challenging. Of key importance is that accomplishment of these objectives could demonstrate usefulness of thermal scanner data in improving our freeze protection techniques, forecasting our freezes, and mapping freeze hazard areas. Success in these 3 areas could save millions of dollars, and minimize the great financial and personal hardships experienced as a result of a severe freeze.

The mission as a whole went smoothly with all research agencies collecting valuable data. The data, particularly from the Recon IV and the PRT-5, however, were somewhat disappointing because of instrument malfunctions. Nevertheless, enough information from the scanner was obtained during the flight to advance our understanding significantly

on a number of the objectives. In particular, the scanner provided valuable information not obtainable any other way, on experiments conducted on various citrus grove heating methods.

Further analysis of the good data obtained and the experience gained relative to the capabilities of the scanner and the data reduction required, should enable future missions of this type to satisfactorily complete the objectives outlined.

PART II - RSI-1 MISSION WITH THE RS-14 THERMAL SCANNER TO
EVALUATE PLANT WATER STRESS CONDITIONS

INTRODUCTION

From energy transfer theory it can be shown that as plant transpiration is reduced by drought, leaf temperature rises to increase heat transfer to the air and thermal radiation to the sky. The degree to which leaf temperature increases with increasing water stress is not clearly understood. Wiegand and Namken showed with a ground-based infrared camera that stressed plant temperatures were higher than nonstressed plants in the imagery (2). Horton, Namken and Ritchie (3) presented data showing (Fig. 6) that near field capacity, crop temperature seldom was more than 2°C above air temperature. However, when average water potential in the surface 1 m of soil was -5.4 bars, leaf temperature could be as much as 6°C higher than air temperature.

Based on this information about leaf temperature, it seems feasible to attempt detection of plant water stress by flying a thermal scanner over test areas where plants are under a variety of stresses. Ultimately this research might provide information to growers on when to irrigate. Proper timing of irrigations would help to provide a quality crop while minimizing water required.

DESCRIPTION OF APPARATUS

An RS-14 scanner was flown by Remote Sensing, Incorporated, Houston, at 2,000 feet over the test area at 1100, 1130 and 1400 on July 7, 1970 and at 1418 on July 8, 1970. Two other flight lines, 10 and 5 miles each were flown in non-test areas. With the exception of one flight, scanner data used to expose the film were from the 8-14 μm channel. Both the 3-5 and 8-14 channels were recorded on analog tape. The scanner was set at 1 mr field of view and 200 scan lines per second were obtained. The internal calibration blackbody sources were set at temperatures above and below that expected for the crops in the agricultural scene viewed.

METHOD OF ANALYSIS

The data were reduced using a microdensitometer in which three main portions of the film were densitized. The areas densitized for each flight line were the cal sources, the grey scales and the field of interest. The fields of main interest were from our Research Farm. The entire 50-acre farm was scanned.

Figure 7 shows the manner in which film density was converted to blackbody temperature. The optical counts for the grey scale steps on the film were converted to film density; these film densities were then plotted versus the corresponding voltage level used to generate each grey scale. The voltages were used rather than using arbitrary numbers such as 1 through 10 for the grey scales, since equal voltage steps are not used (4). The cal source densities and their temperatures were then plotted as shown by the dashed lines. By placing these temperatures on a blackbody temperature scale as shown at the bottom of the figure, it was possible to obtain temperatures corresponding to each grey scale density. Using these sets of values a fourth-degree polynomial was fit to the curve.

The S-shaped curve results from the gamma function of the film. Though it might have been advantageous to have most of the densities shifted somewhat upward on this curve, they are nonetheless in a portion of the curve where temperature changes quite rapidly with film density.

The analog record obtained during the flight on magnetic tape is to be digitized. Once this is finished it will be possible to use programs such as Picout to plot the data. This will allow comparisons between the two methods of data reduction for both speed and accuracy.

RESULTS AND DISCUSSION

Only data from the 7 July 1970 1400 flight of the Research Farm area will be presented. In general, findings from the 1400 flight are typical of those found during other flights.

Figure 8 is a black and white picture of the Research Farm. The research buildings are shown in the lower center portion of the figure. Crop areas are generally dark-toned while bare soil is grey. Cotton

under varying degrees of stress was the main test crop. Cotton plots had been irrigated at two weeks and five days prior to the flight and the third treatment had not been irrigated. In general, the cotton was planted on the south side of the farm and treatments had 3 bare rows between them. They can be seen in the area marked cotton in the upper right-hand portion of the film. Cotton in the lower right hand area has severe root rot. In this area data could be analyzed from only segments of each of the treatments. In the upper center portion of the picture, cotton was under investigation in a separate study (a diagonal line transects this area). The portion below the diagonal had been well irrigated while the upper portion was drier. Another area of particular interest is the lower bare field near the center of the photograph. The right side of this field is slightly darker than the remaining field. The difference is due to tillage underway during the flight.

Figure 9 shows the 1400 thermal film obtained of the Research Farm. In this film, the white areas are the warmest and dark areas are the coolest. It can be observed that the cotton root rot areas are warm since the scanner sees both hot soil and dead plants in those areas. In the cotton area in the upper right hand corner some differences in density are observable. These differences could be picked out very easily with the microdensitometer. Also the cotton field with the diagonal line shows less thermal radiation being emitted by the lower portion. A marked contrast exists in the bare field where the tractor was working. The soil turned up in tilling is cooler than the soil surface and remains cool as long as its water is readily available for evaporation.

An additional treatment in the thermal picture is of interest. This treatment is bare soil which had been irrigated at different intervals. It is just to the left of the cotton field with the diagonal line. We see a hot, intermediate and a cool area in Figure 9. The hottest area had not been irrigated. The middle area had been irrigated five days before the flight and the coolest area had been irrigated the day before the flight. There was no visible difference between the dry and the intermediate irrigation treatment. Thermal radiation differences are observable, however, in the thermal film.

During this flight, ground measurements were taken with thermocouples and a PRT-5. The PRT-5 was mounted on a truck and just before, during and after the flight, it was driven through the farm on a predetermined course to obtain temperatures from the 28 test fields.

These data are compared with that obtained from the thermal film in Figure 10. In Figure 10 if all the points fell on the dash line a one to one relation would exist. The points are observed to cluster close to the 45° line in the 29 to 37°C range. However, for the bare soils which generally had temperatures in the 50 to 60°C range, the scanner data gave temperatures several degrees higher than obtained with the PRT-5. The reason for this discrepancy is not yet clear. It does appear that a straight line could be drawn through the data as shown by the solid line.

We need to know how cotton temperatures obtained from the scanner vary with the moisture stress treatments. Figure 11 shows "crop temperature" as obtained from the thermal film compared with the leaf water potential in bars. Generally, well-watered crops have a water potential during midday of about -10 or -12 bars. Normally for cotton a potential of -20 bars is obtained in the afternoon when irrigation is required. It can be seen from this figure, that in this range of plant water stress, temperatures varied from 30° to 36°. Since there is both a low noise equivalent temperature for this scanner (0.5°C) and a good relation between temperature and stress conditions, it appears that temperature could be used to aid in irrigation timing.

CONCLUSION

The use of thermal imagery in connection with plant water stress appears to hold considerable potential, particularly with scanners such as the RS-14 where internal calibration sources can be adjusted to bracket the temperatures of interest.

The data from the thermal film are fairly easy to reduce; however, data reduction in 3 days or less would be required before it could be used in irrigation timing.

REFERENCES

1. Cooper, W. C., Young, R. H., and Turrell, F. M. Microclimate and physiology of citrus: their relation to cold protection. *Agr. Sci. Rev.* Winter: 3-15. 1964.
2. Wiegand, C. L. and Namken, L. N. Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. *Agron. Jour.* 58:582-586, 1966.
3. Horton, M. L., Namken, L. N., and Ritchie, J. T. Role of plant canopies in evapotranspiration. Presented at the Great Plains Agricultural Council Evapotranspiration Seminar, Bushland, Texas, March 23-25, 1970.
4. Mohr, Don M., Jr. Unique design of the RS-14 multispectral scanning system. *Electro-optical Systems Design Conference Technical Paper.* Texas Instruments, Inc.

Table 1.--The distribution of letters, representing resolution elements, in computer print-out for the third Picout run of the A&I south groves in which "Tree Heet" (TH)-4-1b petroleum coke blocks--and return stack (RS) heaters were burning at overflight time, 0355 hr.

Computer symbol	RS heated area		TH heated area		Bin temp range °C
	No. of elements	% of elements	No. of elements	% of elements	
A	810	57.46	734	81.92	-1.5 to -0.5
B	338	23.85	68	7.60	-0.5 to +1.0
C	55	3.88	18	2.01	1.0 to 1.5
D	38	2.68	16	1.79	1.5 to 2.0
E	17	1.20	15	1.67	2.0 to 2.7
F	17	1.20	9	1.00	2.7 to 3.2
G	10	.71	5	.56	3.2 to 4.2
H	8	.57	8	.89	4.2 to 5.0
I	24	1.69	5	.56	5.0 to 5.8
J	7	.50	3	.33	5.8 to 6.3
K	24	1.69	7	.78	6.3 to 8.4
L	20	1.41	5	.56	8.4 to 10.8
M	27	1.91	0	.00	10.8 to 12.5
N	12	.85	0	.00	12.5 to 14.5
O	6	.42	0	.00	14.5 to 15.4
P	4	.28	3	.33	> 15.4
Totals	1417	100.00	896	100.00	

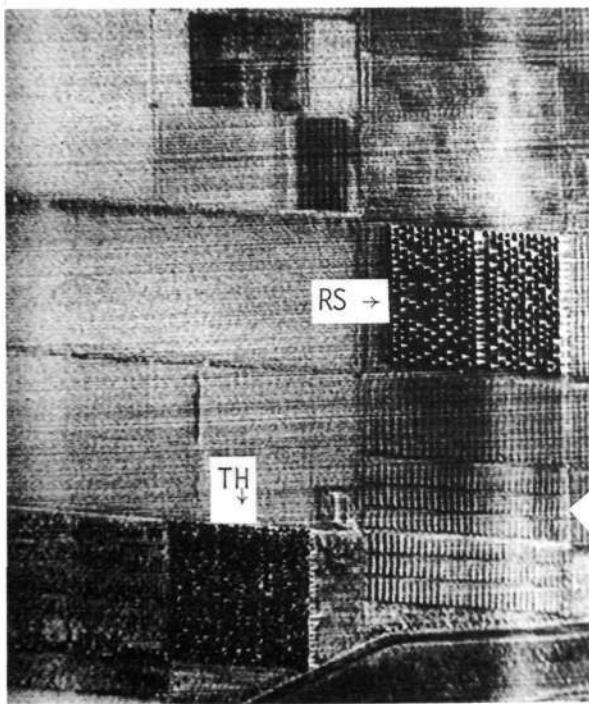


Figure 1.- Thermal image produced in flight, A&I south grove, 1/8/70, 0355 hours. (TH - area heated with Tree Heet, RS - area heated with return stack heaters.)

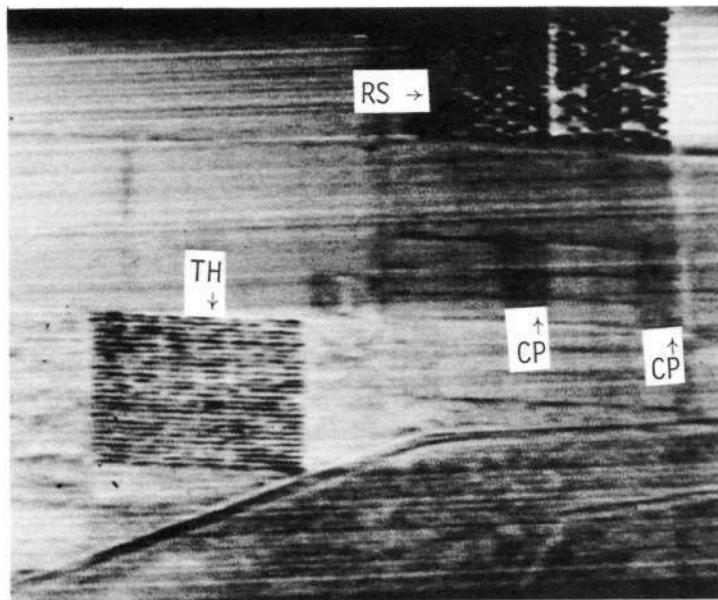


Figure 2.- Thermal image of analog magnetic tape displayed on CRT of same area as Fig. 1. (TH - area heated with Tree Heet, RS - area heated with return stack heaters, CP - cultural practice temperature effect.)

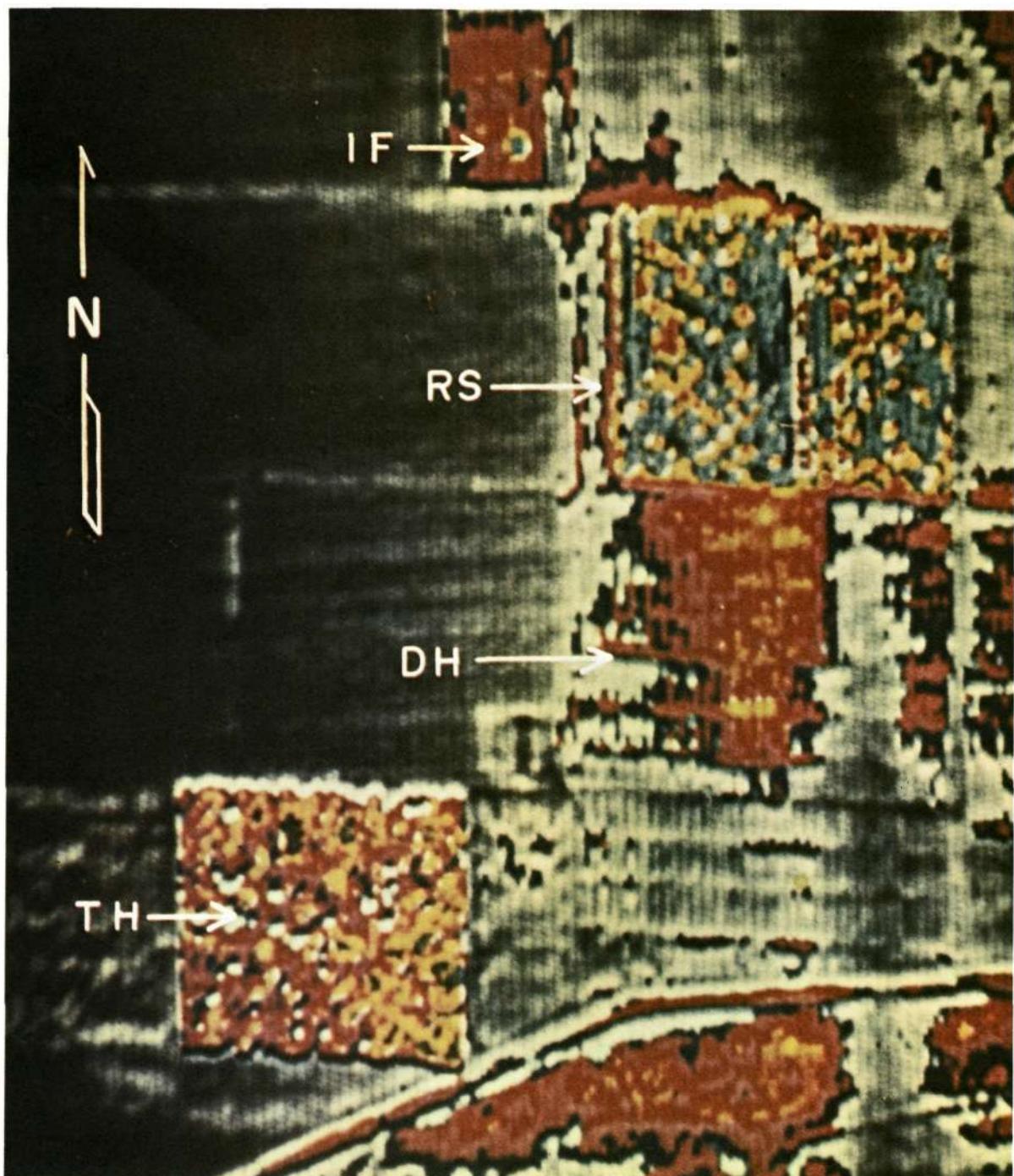


Figure 3.-Image transparency of Fig. 1 displayed on a color enhancing DATACOLOR SET. (TH - area heated with Tree Heet, RS - area heated with return stack heaters, DH - downwind heated area, IF - irrigated field.)

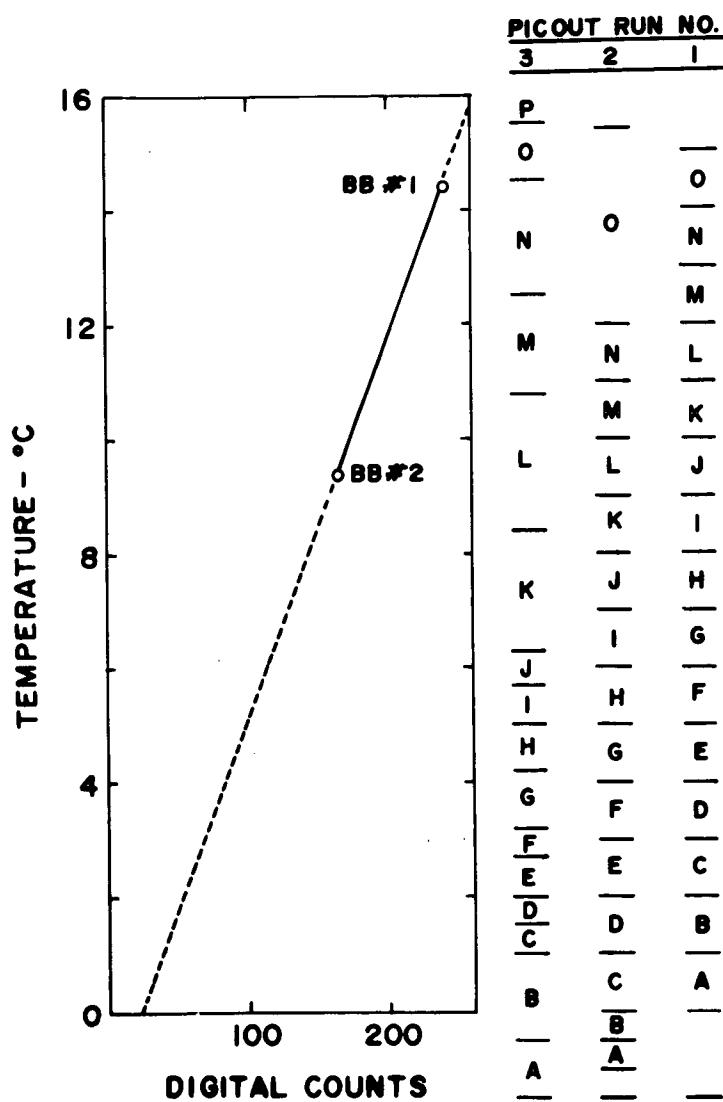


Figure 4.- Temperature versus digital counts showing the position of the blackbody (BB) cal source temperatures. Superimposed on the temperature scale are the symbols used for the computer printout of each bin in the Picout program for Picout runs 1, 2, and 3.

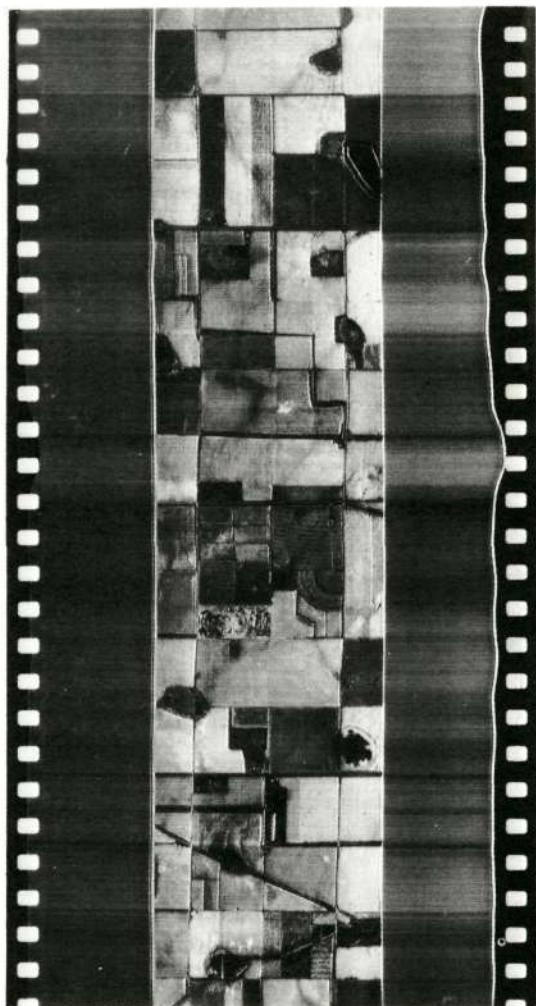


Figure 5.- Thermal image produced in flight (line 6, flight 2, 0000 hours, 1/8/70) showing the considerable thermal (irradiance) contrasts occurring in the agricultural scene overflown.

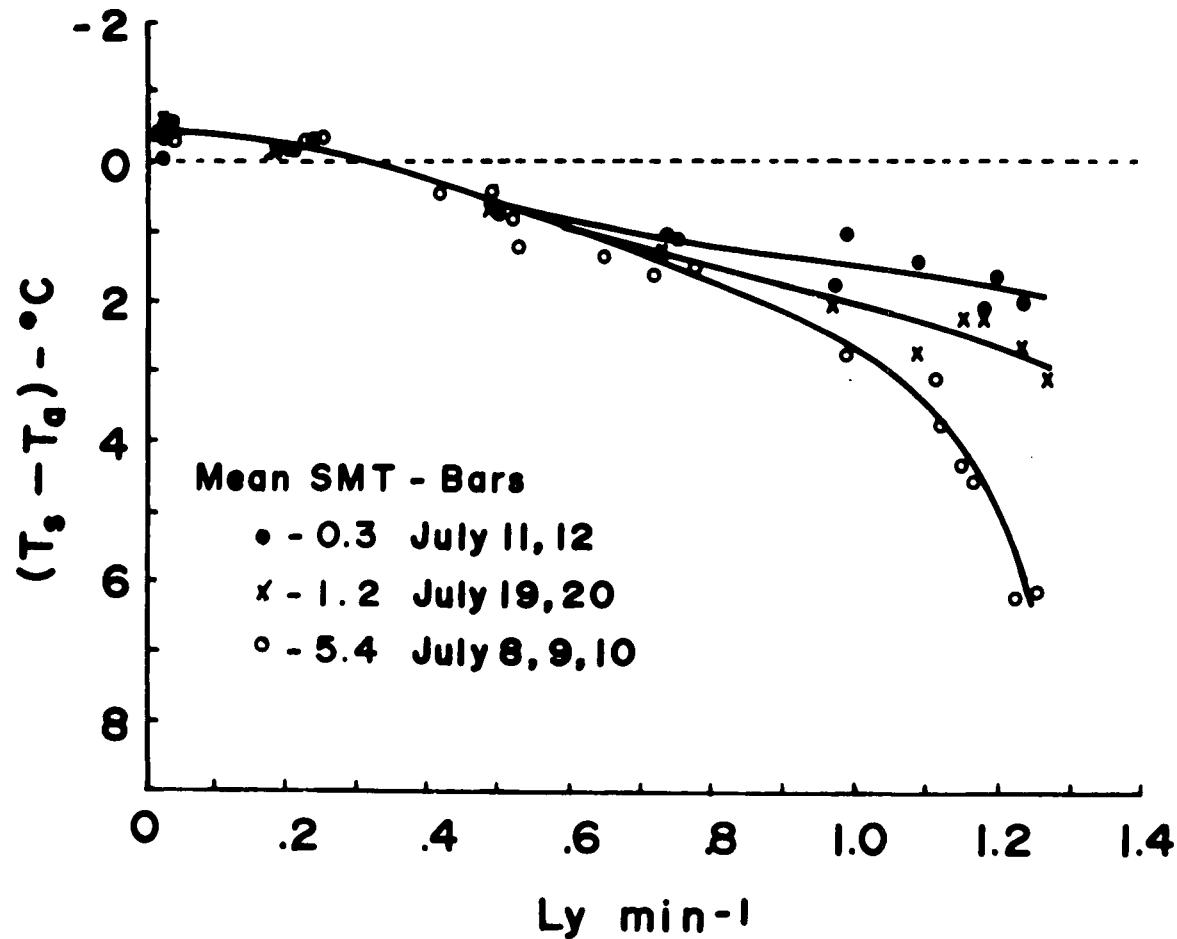


Figure 6.- Relation of the difference between crop surface and air temperatures ($(T_s - T_a)$) to solar radiation at various mean soil moisture tensions (SMT) for the top meter of soil.

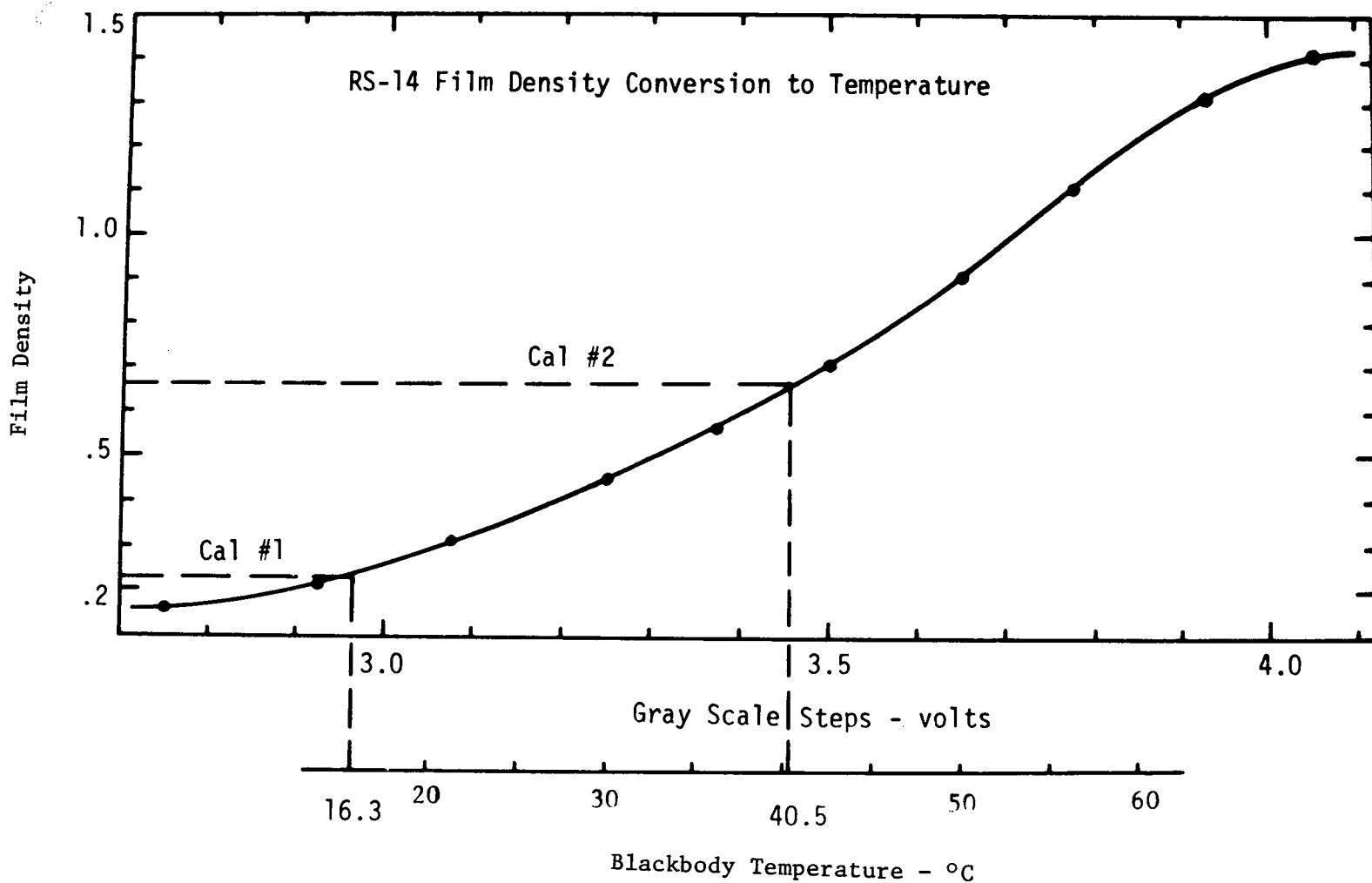


Figure 7.- Film density versus grey scale step voltage and blackbody temperature, RS-14 scanner. (Film density of the 10 grey scale wedges and the voltages of each were used to construct the curve. Then, using the measured density of the cal sources and their known temperature, a relation between film density and blackbody temperature was obtained.)

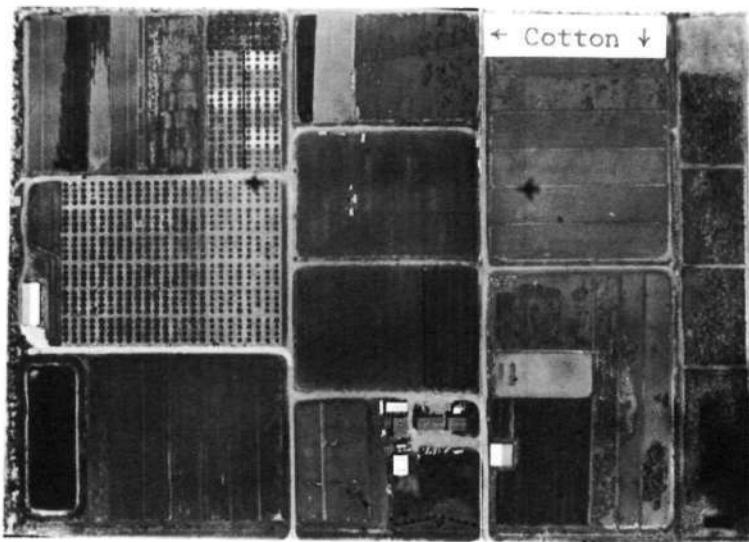


Figure 8.- Ektachrome IR picture of the Research Farm.

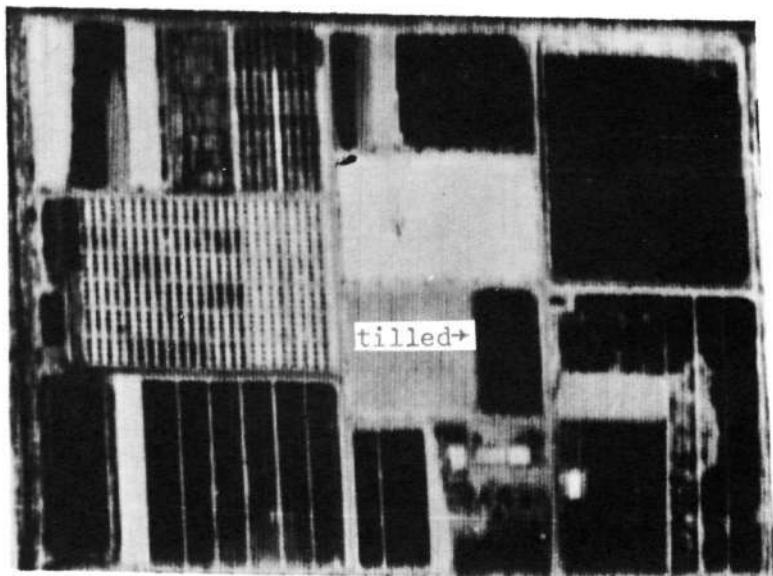


Figure 9.- Thermal image obtained for the Research Farm. Dark-toned objects are cool, light-toned objects are warm.

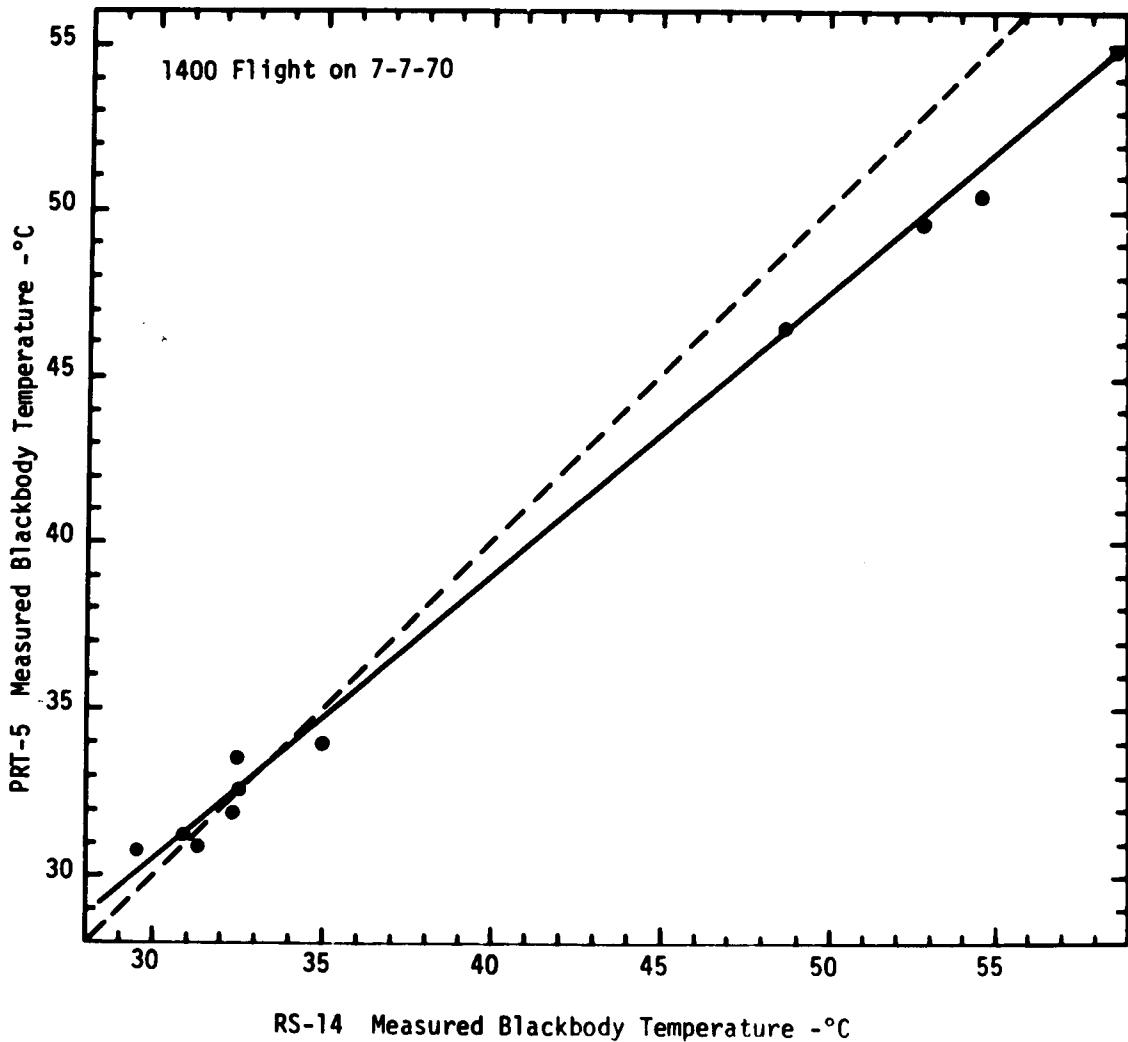


Figure 10.- Relationship between PRT-5 temperature measurements taken from the ground and temperatures obtained from RS-14 data.

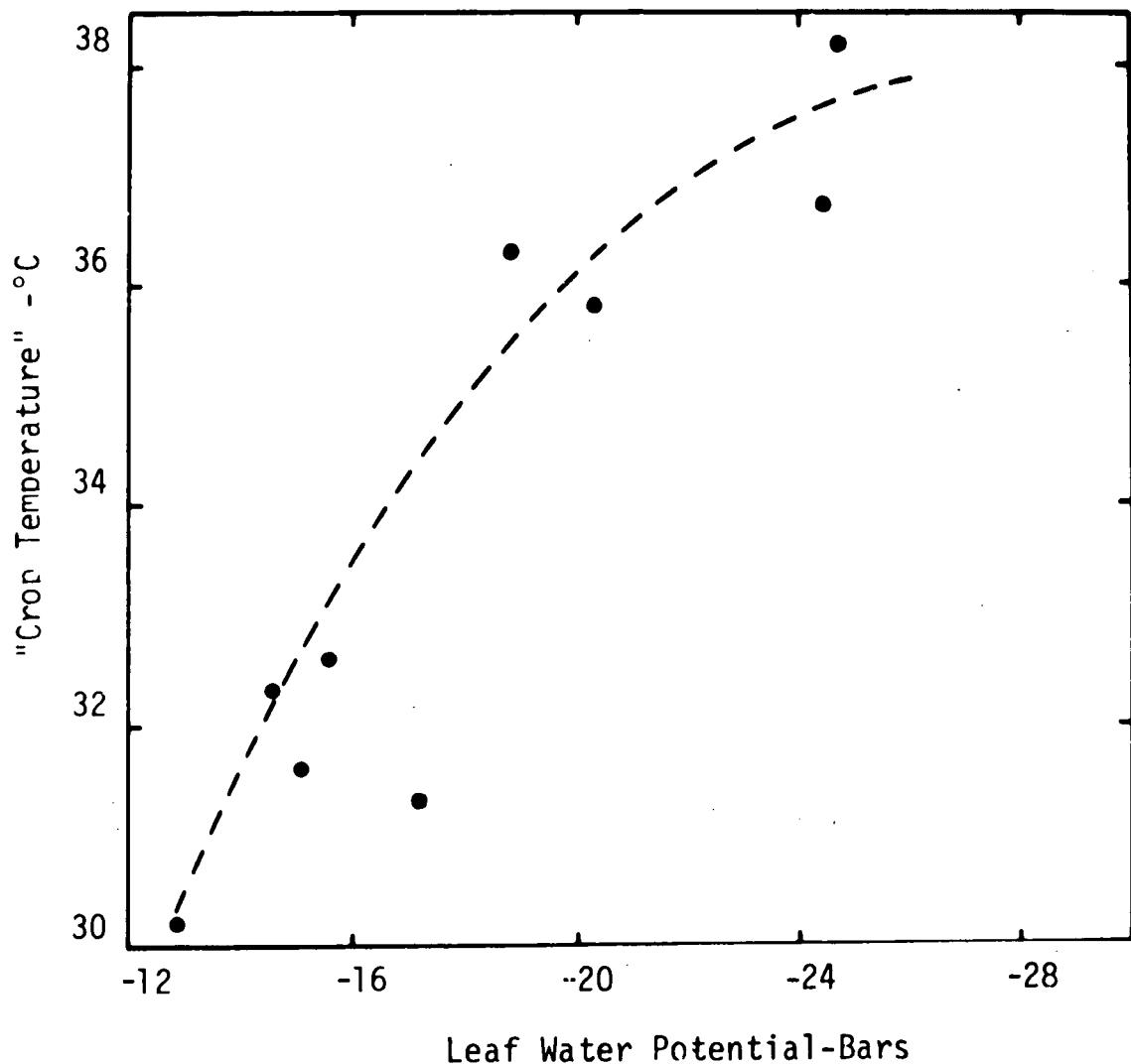


Figure 11.- Relation between cotton leaf emittance (8-14 μm) measured with an RS-14 scanner and plant stress.